APPENDIX A

First Paper:

Evidence for a New Force in Halo Nuclei

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ABSTRACT

A model is made of a halo nucleus with a single nucleon orbiting the core nucleus in a new central potential, like a miniature hydrogen atom. We solve the Schrödinger equation for five halo nuclear states with unambiguous quantum numbers, and find that the same force is required to bind the neutron states as the proton states (allowing for the Coulomb repulsion). These five states are consistent with the existence of a single force with the coupling constant $\alpha_c = 0.043 \pm .005$, which is 5.9 times stronger than electromagnetism, over distances of order ten fermis. This new force has the same strength at 300 keV as the Unified Field at 10^{16} GeV, which implies a direct relationship between these two. This force and its properties are evidence for physics beyond the Standard Model.

Introduction

In this paper we present evidence for a nuclear force, which has a range that is an order of magnitude greater than that of normal nuclear forces. This means that this new force **cannot** be caused by any known nuclear force, because its range is too long, and therefore it could be a new force of nature.

The defining feature of the strong interaction, which is believed to be the source of all nuclear forces, is that it is *confined* within nuclei and elementary particles. It is the central assumption of QCD that colour and gluons are confined. If attempts are made to get around this, they fail. For example, if one explores the alternative hypothesis that quarks are confined but colour and gluons can be free, one runs into inconsistencies with the data.[1] Both colour and gluons have to be confined within hadrons and nuclei. *Therefore, if one observes a nuclear force acting beyond the surface of hadrons or nuclei, it cannot be the normal strong interaction, and has to be a new force of nature.*

We now show evidence for such a "long-range" nuclear force in halo nuclei.

Halo Nuclei

In nuclear physics, a halo nucleus is an unusual nucleus with a diffuse halo of hadronic matter around it. A normal nucleus is like a liquid drop, with a constant density in the interior and a sharp drop in the density to zero at the surface. In the last decade it has been discovered that diffuse "nuclear halos" can exist outside the central core of the nucleus, that is, beyond the surface of the "liquid drop" of normal nuclear matter. Nuclear halos are regions outside the surface of a nucleus, where the nuclear density is much reduced, but it is not zero. As one moves away from the nucleus, the halo density decreases much more slowly than the sharp cut-off at the surface of a normal nucleus. Halo nuclei have much larger cross-sections than normal nuclei, and there is ample evidence that they consist of a nuclear core with one or more nucleons outside the core, which are weakly bound to it.

Halo nuclei were first discovered by Tanihata and colleagues working at the Lawrence Berkeley Laboratory in 1985.[2] They have a larger cross-section than normal nuclei, and the halos typically extend to two to three core-nuclear radii or more.[3] They are physically larger than normal nuclei. For example, ^{11}Li is found to consist of a ^{9}Li core surrounded by a halo of two neutrons at an rms radius of about 7 fm, compared to the radius of the ^{9}Li core of 2.3 fm. The binding energy of the neutron pair is only 310 keV, compared to 10 to 30 MeV for a pair in a stable nucleus. Examples of halo nuclei are given in table 1.

Table 1: Examples of Halo Nuclei

Nucleus	E_x (MeV)	$S-E_x$ (keV)	Configuration	ℓ	$\langle r^2\rangle^{1/2}$ fm
^{11}Be	g.s.	504	$n + {}^{10}Be$	0	5.9, 6.58*)
^{11}Be	0.32	184	$n + {}^{10}Be$	1	5.35
^{25}Ne	4.07	90	$n + {}^{24}Ne$	?	5.26
^{8}B	g.s.	137	$p + {}^{7}Be$	?	-
^{17}F	g.s.	600	$p + {}^{16}O$	?	3.9
^{17}F	0.50	105	$p + {}^{16}O$	0	4.4, 5.74*)
^{21}Na	2.42	7	$p + {}^{20}Ne$	0	4.25, 5.65*)
^{6}He	g.s.	973	$n + n + {}^{4}He$	-	-
^{11}Li	g.s.	310	$n + n + {}^{9}Li$	-	-

*) Values for the 0s and 1s states respectively.

where S is the separation energy.[4] Both the ground state and excited states of ^{11}Be and ^{17}F are halo nuclei. There are several reviews of the subject.[5] Note that the binding of these halo nucleons to the core nucleus, cannot easily be explained in terms of the Yukawa interaction, because of its short range of 1 fermi.

Properties of Halo Nuclei

Before we make a model of these halo nuclei, let us briefly consider their properties. Halo nuclei are produced when a beam of ordinary nuclei is collided with a target of ordinary nuclei to produce a beam of unstable isotopes by means of projectile fragmentation. This radioactive nuclear beam so produced is scattered off a secondary target. By developing this technique, it has become possible to make measurements on highly unstable nuclei at the limits of nuclear stability, where these nuclei are to be found.

The halo nucleons of these nuclei are found to be in states of low orbital angular momentum, typically s and p states. The halo nucleons are in weakly bound diffuse states, which have been observed to stretch out to 25 fm from the core nucleus. And as a result they appear to be almost independent of the core nucleus, as the following evidence shows.

One of the distinctive experimental features of these halos, which also shows the independence of the halo nucleons from the core nucleus, is *the narrow momentum distribution of the halo nucleons*. The momentum distribution is found to be *one tenth to one fifth* that of nucleons inside a normal nucleus, *which shows that they are mechanically decoupled from the motion of the nucleons inside the core nucleus.* This narrow momentum distribution is so distinctive that it is now used experimentally to detect new halo nuclei.

There is a considerable amount of additional evidence which shows that the halo neutrons are, to a good approximation, almost independent of the core nucleus.[6] Firstly, in a halo with two or more nucleons, protons and neutrons are physically separated and decoupled, so that electric dipole excitations are those of single particles. Secondly, at very low energies the Giant Dipole Resonance is no longer dominant, again showing that they are decoupled. Thirdly, the E1 transition probabilities are of the order of a single particle rate. This is shown by Coulomb stripping reactions on high-Z targets, where at very low energies, the cross-section for the removal of two neutrons from ^{11}Li is 5.0 ± 0.8 barns, which is two orders of magnitude larger than normal Coulomb excitation reactions.[7] Fourthly, beta decay occurs at single-particle rates similar to "super-allowed" transitions. For example even-n nuclei along the neutron drip line, show fast beta transitions with a strength and energy which suggests that they come from the decay of quasi-free neutrons.[8] Thus the halo nucleons are not actually inside a nucleus. This evidence suggests that one is in fact observing "atoms" with single nucleons orbiting a core nucleus, and it would be more appropriate to call them "hadronic atoms" or "nuclear atoms".

The reduced momentum distribution of these halo nucleons is so significant that more details are relevant. Early experiments to measure the momentum distribution of the halo neutrons showed

that it is about 25 MeV/c, which is one tenth that of neutrons bound strongly into normal nuclei. The data shows a "twin peak" structure, with a narrow peak (54 $\pm$ 12 MeV/c FWHM) from the halo neutrons, sitting on a broad background (223 $\pm$ 28 MeV/c FWHM) due to neutrons from the core nucleus.[9] This twin peak structure has been observed in other experiments and is now considered a sign for a new halo nucleus. Careful experimentation to measure the *longitudinal* momentum distribution of the ^{9}Li core from the breakup of ^{11}Li on a target nucleus, shows that the momentum distribution of the halo neutrons is about 60 MeV/c FWHM, which is about one fifth the width obtained in the fragmentation of a normal nucleus.[10] The results of a number of experiments show that the momentum distributions of halo nucleons are in the range 25 to 60 MeV/c which is one tenth to one fifth that of nucleons bound inside a normal nucleus. *Thus the halo nucleons are mechanically decoupled from the core nucleons.*

This reduced momentum distribution can be related to the size of the halo nucleus. The Heisenberg uncertainty principle requires that as the size of the nucleon halo increases, so the uncertainty in the momentum decreases. The narrow momentum distributions observed agree in this way with the large rms radii of the halo nuclei measured.

If one considers the evidence in the preceding paragraphs, it is quite clear that *halo nucleons behave like independent particles orbiting the core nucleus.* It is thus quite logical to explore the possibility that the halo neutrons are described by a separate wave function from those of the core neutrons, and are in fact bound to the core by a separate nuclear force.

Before we do this, we mention that current theoretical explanations of halo nuclei assume that they are due to the tail of the wave function which can extend quantum mechanically beyond the surface of a square-well potential.[11] However, it is difficult to construct models which describe all the above properties, *particularly the narrow momentum distributions*, without invoking other effects, such as break-up interactions.[12] In other words, assuming that halo nuclei are due to the tail of the nucleon wave function is not a straight forward explanation, but a ptolemaic one, where increasing levels of complexity have to be introduced to get the theory to fit the data. We therefore use Ockham's razor to reject this 'explanation', and construct the following simple model. We assume that the halo nucleons move in a new central potential due to a new long-range force of nature, around the core nucleus.

The Central Potential Model

We assume that there is a new force with a new type of charge which can be carried by hadronic matter. For simplicity, we apply this to single-nucleon halo nuclei only. We assume that the single halo nucleon is orbiting the core nucleus under the influence of this new central potential. We assume that when a core nucleus and a halo nucleon both carry one or more of the new charges with the appropriate sign, then they will be attracted to each other by this new force. (If one or both do not carry the new charge, then they will not interact via the new force.) We assume that the new force obeys an inverse-square law, at least over these short distances of a few tens of fermis. One then has a system like an hydrogen atom, in which a halo nucleon (electron) orbits the core nucleus in a central potential.

The main differences are that such an hadronic atom will be smaller than an hydrogen atom, and the nucleus larger than a proton, so that the core-nucleus will hardly be point-like. *However, for low values of the quantum numbers of the halo nucleon, its wave function will be excluded from the core nucleus by the exclusion principle, because these states will already be occupied by nucleons inside the core nucleus. Thus the halo nucleon will be decoupled from the nuclear core by the exclusion principle.* Therefore, we assume that the core nucleus is point-like. Thus the halo nucleons are moving in a central potential around a point-like core nucleus, and are described by separate wave functions, orthogonal to those of the core nucleons. This enables the halo nucleons to have a different momentum distribution from that of the core nucleons.

This model of an hadronic atom then approximates to that of an hydrogen atom, except that the mass of the halo neutron is much larger than that of an electron; the coupling constant α_c of this hypothetical new force is different from the fine structure constant; and the charges c of this force are different from the electron charge.

The Model for a Neutron Halo Nucleus

We consider ^{11}Be as a two-body system, with the core being ^{10}Be orbited by a single neutron. The Hamiltonian for this halo nucleus can then be written as follows:

$$H = \frac{-\hbar^2}{2(m + M)}\nabla^2_{CM} - \frac{\hbar^2}{2m_r}\nabla^2 - \frac{C_N C_n \alpha_c \hbar c}{r} \qquad (1)$$

where m is the neutron mass, M is the core nucleus mass, m_r is the reduced mass, C_N and C_n are the numbers of the charges for this new force on the nuclear core and the halo neutron respectively, and α_c is the coupling constant for this new force. If one writes down the Schrödinger equation for this Hamiltonian and solves it, one finds that the energy levels are given by:

$$E_n = \frac{C_N C_n \alpha_c^2 m_r c^2}{2n^2} \qquad (2)$$

We can then use the values for the energy levels of ^{11}Be given in the table above to determine the coupling constant α_c. But first we have to choose the quantum numbers unambiguously. For the ground state of ^{11}Be, n = 1 (there is no other choice for the ground state). The simplest choice on probability grounds for the charge quantum numbers is $C_n = C_N = 1$. This minimum set of quantum numbers is unambiguous, and one gets $\alpha_c = 0.034$ for the ground state of ^{11}Be.

The excited state of ^{11}Be appears to be the first excited state (no other intermediate states reported), and so one has to set n = 2. Using the minimum charge values ($C_n = C_N = 1$) for the reasons given above, one gets $\alpha_c = 0.041$ for the first excited state of ^{11}Be. Note that we have excluded ^{25}Ne from this analysis because we do not know its principle quantum number.[13]

There is a 20% difference between these two values of α_c, which presumably reflect the approximations made in the model, for example that the core nucleus is point-like. So we shall use the average value $\bar{\alpha}_c^n = 0.038 \pm .005$. These results are shown in table 2 below.

The Bohr radius for the system is given by $a_o = \hbar c/\alpha_c m$. Putting in the above value for α_c, we find the Bohr radius of the system to be 5.5 ± 0.7 fermis, which agrees with the observed halo sizes given in table 1. The wave function in momentum space is the Fourier transform of the spatial wave function, and the root-mean-square momentum corresponds to that of the Bohr radius.[14] This Bohr radius of 5.5 fermis corresponds to an rms momentum of the halo neutron of 36 ± 5 MeV/c. The full-width-half-maximum of the momentum distribution projected onto one axis is of the same order of magnitude, and is compatible with the measured values of 25 to 60 MeV/c mentioned above. We thus see that the results of this calculation, namely the spacial extent of the wave function and the momentum distribution of the halo neutron, are compatible with the uncertainty principle and in agreement with the experimental data.

Table 2: Coupling Constant for Neutronic Hadronic Atoms

Nucleus	E_x (MeV)	S-E_x (keV)	Core	n	C_N	α_c
^{11}Be	g.s.	504	^{10}Be	1	1	0.0343
^{11}Be	0.32	184	^{10}Be	2	1	0.0415
Average						0.038 ± .005

The Model for a Proton Halo Nucleus

The above result encourages us to apply this model to the single-proton halo nuclei given in table 1. In addition to the above proposed new force, a proton outside a core nucleus will also experience an electrostatic repulsion from the core. Thus the potential energy will be given by:

$$V(r) = -\frac{C_N C_n \alpha_c \hbar c}{r} + \frac{Z\alpha\hbar c}{r} \qquad (3)$$

where Z is the electric charge on the core nucleus, and α is the fine structure constant. The proton

will only be bound if the attraction due to this new force is greater than the Coulomb repulsion:

$$C_N C_n \alpha_c > Z\alpha \tag{4}$$

If we put the above potential into the Hamiltonian for this protonic hydrogen atom and solve the corresponding Schrödinger equation, we obtain the following energy level spectrum:

$$E_n = (-C_N C_n \alpha_c + Z\alpha)^2 \frac{m_r c^2}{2n^2} \tag{5}$$

If we solve this subject to the condition above for bound states, we find:

$$\alpha_c = \frac{Z\alpha}{C_N C_n} + \frac{n}{C_N C_n}\sqrt{\frac{2E_n}{m_r c^2}} \tag{6}$$

In order to solve this equation for the protonic halo nuclei in table 1, we have to choose the quantum numbers of the new force. For the ground state of ^{8}B, one has quite unambiguously n = 1. In order to choose the numbers of new charges, we now have the constraint given in equation (4). In the case of the core nucleus ^{7}Be, $Z\alpha$ is 0.029. If we use the value for the coupling constant that has already been determined above from the neutron halo data ($\bar{\alpha}_c^n = 0.038$), the condition in equation (4) can be satisfied for $C_N = C_n = 1$, although larger values are not excluded. We then choose the minimum values ($C_N = C_n = 1$) for the reasons given above. With the quantum numbers so determined, we find $\alpha_c = 0.0471$ for ^{8}B, as shown in the table 3 below.

The next nucleus, ^{17}F, provides an interesting test of our model. Z = 8 for the core nucleus ^{16}O, and $Z\alpha = 0.058$. If the value of the coupling constant lies in the range already determined above ($\alpha_c = 0.038$ to 0.0471), then equation (4) cannot be satisfied for $C_N = C_n = 1$. In simple terms, the eight electric charges on the core oxygen nucleus are repelling the proton with a force that is stronger than the binding produced by a single charge pair of the new force which appears to be only 5 or 6 times stronger than electromagnetism. However, the condition in equation (4) is satisfied if $C_N = 2$ and $C_n = 1$, or vice versa, although larger values are not excluded. We choose these minimum values that satisfy equation (4), for the reasons given above.

For the ground state of ^{17}F, we have to choose n = 1. Having now determined the quantum numbers unambiguously, we find $\alpha_c = 0.0476$.

For the first excited state of ^{17}F, we have to choose n = 2. Furthermore, if the proton is to be bound, we have to choose $C_N = 2$ and $C_n = 1$, or vice versa, for the reasons given above. We then find that $\alpha_c = 0.0446$. (We have excluded ^{21}Na from this analysis because its principle quantum number is undetermined.[15])

Note that there is no choice in the quantum numbers if the proton is to be bound. The binding energy of the first excited state of ^{17}F is quite low (105 keV), yet the results from the three protonic hadronic atoms agree very well, in fact uncannily well, as shown in table 3.

These results for protonic atoms have a greater consistency over the results for neutronic atoms. This could be explained by the more efficient exclusion of the proton wave function from the core nucleus by the Coulomb repulsion, so that a halo proton is less likely to be perturbed by core nucleons than a halo neutron. We find that the average value for the protonic hadronic atoms is $\bar{\alpha}_c^p = 0.0464 \pm .002$.

Table 3: Coupling Constant for Protonic Hadronic Atoms

Nucleus	E_x (MeV)	S-E_x (keV)	Core	n	C_N	α_c
^{8}B	g.s.	137	^{7}Be	1	1	0.0471
^{17}F	g.s.	600	^{16}O	1	2	0.0476
^{17}F	0.50	105	^{16}O	2	2	0.0446
Average						0.0464 ± .002

Results

If we now compare the mean value of the coupling constant of this new force for the neutronic nuclear atoms, $\bar{\alpha}_c^n = 0.038 \pm .005$, with that from the protonic nuclear atoms, $\bar{\alpha}_c^p = 0.0464 \pm .002$, we see that they are equal to within the experimental errors. The neutronic atoms give a slightly lower value by about 1.5 standard deviations, which is presumably due to approximations in the model. If one compares the five estimates of the new coupling constant given in tables 2 and 3, one sees that they are the same, within the errors. We therefore average the five values to get the best estimate of this new coupling constant.

We find $\bar{\alpha}_c = 0.043 \pm .005$

Since these calculations have been done, our attention has been drawn [12] to a sixth halo nucleus ^{19}C, which is a single neutron halo nucleus with a single neutron separation energy of 240 $\pm$ 100 keV.[16] The principle quantum number is found to be n = 2,[17] so that $\alpha_c = 0.0464 \pm .010$, which is compatible with the above results within these large errors, and so provides additional confirmation. (The large error in this data point means that it does not contribute any significant precision, and so we choose to exclude it from the final average.)

The above six values of the coupling constant are consistent with the above average value, therefore the hypothesis that there is a single central potential binding these halo nucleons appears to be valid.

Discussion

1. The coupling constant of this central potential is 5.9 times that of electromagnetism. Therefore the force behind this phenomenon cannot be the electromagnetic, weak or gravitational interactions because they are too weak. Furthermore, it is far too strong, by many orders of magnitude, to be one of the forces predicted by Dimopoulos and Giudice.[18]

2. The only known force strong enough to produce this potential, is the strong interaction, which also couples to hadrons as required here. However, this has far too short a range to produce this potential. The Yukawa interaction has a range of only one fermi and is therefore eliminated. The colour interaction could be the source of this potential, if gluons could have a range of order ten fermis or more (even if quarks remained confined). However, Kogan has pointed out quite forcefully that gluons have to remain confined or the π° could decay to gluons, which would change its decay rate. QCD currently predicts this decay rate correctly without gluons. QCD also predicts proton-antiproton annihilation correctly, again without free gluons. For these and other reasons, gluons have to be confined within nuclei or hadrons and have a range less than one fermi. *Therefore they cannot explain the above force.*

3. *We are thus forced to conclude that this central potential is due to a new force of nature, which is approximately six times stronger than electromagnetism and has a range of at least ten fermis, but not infinite range.* In the above model, we have used an inverse square law, which implies that this new force has an infinite range. We are **not** suggesting that it really has infinite range. The use of a 1/r potential in this model is just a simplifying assumption. Presumably at longer distances, it must cut off to low values and eventually go to zero. It is a force, since it does work. But whilst it is long-range compared to the strong interaction, it is not long-range in the sense that gravitation or electromagnetism are. Strictly speaking it is an "intermediate range force".

4. For reasons that are not apparent, we call this new force the "order force".

5. The reader may wonder why, if such a force exists, it has not been observed before. We suggest that it has not been observed before because: a) it has unusual properties; b) it is masked by strong interaction processes; and c) because it is not expected theoretically. We now elaborate these reasons.

6. It is clear that this new force has unusual properties. It is not confined to the nucleus or to elementary particles, but it has a limited range. Most matter appears to be neutral with respect to the charge of this force, or its effects would have been more widely observed. Some of its effects may have been observed, but misinterpreted, as in the case of halo nuclei. Furthermore, we do not know

all its properties.
7. In addition, there are good reasons to believe that most of the effects of this new force would be masked by the strong interaction for the following reasons:
a. The strength of this new force is only 0.3% (1/350) that of the Yukawa interaction, and therefore it's effects would have been hidden in normal nuclear reactions.
b. Its effects have not been observed in high energy physics because they would also have been hidden by the strong (colour) interaction.
c. Furthermore, its effects are intermediate-range of several fermis, whilst the main thrust of high energy physics has been to study much shorter distances.

For these reasons, the effects of this force would have been simply invisible in most nuclear and particle physics experiments.
8. Thus there are quite good reasons why this new force may not have been recognized before. Never-the-less, the reader may still find it difficult to accept that this force really exists. In the appendix to this paper we give details of a number of major scientific discoveries which initially failed. The discoveries of parity violation, the neutron, the positron and the microwave background radiation of the Universe, all failed initially for theoretical reasons. It is as if the scientific method has a theoretical bias. In each case, observations of the effect were made, but these were not recognized for theoretical reasons. Only when theory and experiment matched, was the discovery made. Sometimes this occurred years after the original observations were made.
9. The Standard Model has been quite successful in explaining known physics with just four forces of nature, that the existence of a fifth force seems unlikely. However, this force could be evidence for physics beyond the Standard Model. If a new theory, such as string theory, predicted the existence of this force, this could change this situation and the discovery would be made.

We now present a piece of information which suggests that this result does indeed involve physics beyond the Standard Model.

Comparison with the Unified Field

We now draw the reader's attention to the following fact. The value of $\bar{\alpha}_c = 0.043 \pm .005$, which we have obtained above, is almost the same as the strength of the Unified Field obtained from a minimal susyGUT calculation and data from LEP. In this calculation, LEP data has been extrapolated to the unification energy at 10^{16} GeV using a minimal susyGUT, and this gives $\alpha_s(Q^2) \rightarrow \alpha_{GUT} = 0.04 \pm 0.003$ at $10^{16\pm0.3}$ GeV.[19] This value agrees with our value precisely, within the errors:

$$\Delta\alpha = \alpha_c - \alpha_{GUT} = 0.003 \pm .0058$$

which is effectively zero within the errors. Thus we have found that:

$$\bar{\alpha}_c(300 \text{ keV}) \equiv \alpha_{GUT}(10^{16} \text{ GeV}) \quad (7)$$

This result suggests that there is some connection between this new force and the Unified Field. We have found evidence for a new force with the same strength as the Unified Field, which implies some kind of direct relationship between the two. This is clearly physics beyond the Standard Model. Furthermore, this result implies that the correct theory will be a Unified Field theory, such as string theory.

Conclusions

We present evidence from halo nuclei for a new force of nature with a coupling constant of $\bar{\alpha}_c = 0.043 \pm .005$, which is the same as that of the Unified Field. This is evidence for physics beyond the Standard Model. We conclude that the correct theory of this new force, which we call the "order force", is going to be a Unified Field theory such as string theory.

Appendix: Examples of Failed Scientific Discoveries

Let us consider the following major scientific discoveries which initially failed:

1. Parity violation was initially observed in 1928, but it was rejected as "an instrumental effect" because it was contrary to the theory of that time. Then in 1956 Lee & Yang, two eminent theoretical physicists, said that parity might be violated and Mme Wu "discovered" it shortly after that.
2. Irène Curie and Frédéric Joliot failed to discover the neutron because they refused to believe Rutherford's hypothesis that the neutron should exist. The Joliot's published a paper on January 18th, 1932, which showed peculiar effects, which the Joliot's thought were due to photons. However, Chadwick believed in Rutherford's hypothesis and realized that this data was probably showing evidence for the existence of neutrons. So it was Chadwick who discovered the neutron a few months later and won the Nobel Prize, not the Joliot-Curies.
3. The Joliot-Curies also failed to discover the positron. When Carl Anderson discovered it in 1932, the Joliot-Curies discovered that they had already taken pictures of positron tracks!
4. Effects of the microwave background radiation from the Big Bang were first observed by E. McKellar in 1941, but were misinterpreted. In the 1950s, a young Soviet scientist, T.A. Shmaonov rediscovered this radiation for a second time, and determined its temperature to be 4 ± 3 °K. He published this in his thesis in 1957, but nobody appreciated the significance of this. Finally in 1964, Penzias and Wilson rediscovered this blackbody radiation and had the good fortune to meet Dicke at Princeton who explained that this data was the after-glow of the Big Bang. At that point, they made a discovery.

In the first case, theory forbade the observed effect, so it was rejected. In the second case, belief in the wrong theory led to failure to discover the neutron. In the third case, failure to apply Dirac's theory of the positron led to failure to interpret the data correctly, and the discovery was missed. Likewise, in the fourth case, it was only when the theory of the Big Bang was applied to the microwave data that the otherwise meaningless result became a scientific discovery. *This shows that matching the correct theory to the data can be an important part of making a scientific discovery.* Einstein once said "It is the theory which decides what we can observe".[20] For this reason, when theory is wrong, we may find it difficult to observe the evidence which would prove the theory wrong. There are no doubt other examples of this.

Einstein also wrote, "Even scholars of audacious spirit and fine instinct can be obstructed in the interpretation of facts by philosophical prejudices".[21] We therefore have to clear away all theoretical prejudice from the Standard Model that there are only four forces of nature. If we find a new theory which predicts the existence of this new force with the required strength, then we have the scientific discovery of the order force.

References

1. For example if quarks are confined but colour and gluons can be free, then the π° decay rate would change in QCD (because they could decay to gluons), and proton-antiproton annihilation would be different. QCD currently predicts the π° decay rate correctly, assuming that it cannot decay to gluons. QCD also describes proton-anti-proton annihilation correctly, without free gluons. Therefore gluons have to be confined and cannot produce intermediate- or long-range effects (ie > about one fermi). I thank Kogan at Oxford for a useful discussion on this.

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3. J.S. Al-Khalili et al, *Phys. Rev. C* **54**, 1843-1852 (1996); and *Phys. Rev. Lett.* **76**, 3903-3906 (1996). Note that hypernuclei are a separate phenomena. The Λ° is more tightly bound (typically 4 - 6 MeV) to the nucleus than halo neutrons are to the core nucleus. Furthermore, hypernuclei have been explained in terms of existing physics. R.H. Dalitz, private communication.

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11. R.B. Leighton, *Principles of Modern Physics* (McGraw-Hill, NY, 1959), p 154.

12. G Thomson, Surrey University, private communication.

13. It appears to be n = 3, but one needs to identify the first two states to be certain.

14. B. Podolsky & L. Pauling, *Phys. Rev.* **34**, 109 (1929).

15. If the ground state and first few excited states of ^{21}Na could be identified, then one could investigate the form of the interaction more precisely, whether it is 1/r as assumed here, or some other form. This comment applies to ^{25}Ne or other nuclei where several states can be observed.

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